Black holes, string theory and quantum coherence [a]

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On the basis of recently discovered connections between D-branes and black holes, I show how the information puzzle is solved by superstring theory as the fundamental theory of quantum gravity. The picture that emerges is that a well-defined quantum state does not give rise to a black hole even if the apparent distribution of energy, momenta, charges, etc. would predict one on classical grounds. Indeed, geometry - general relativistic space time description - is unwarranted at the quantum microstate level. It is the decoherence leading to macrostates (average over degenerate microstates) that provides - on the same token - the loss of quantum coherence, the emergence of a space time description with causal properties and, thus, the formation of a black hole and its Hawking evaporation.

Many extraordinary coincidences between string theory and black hole physics have been recently uncovered and different opinions have been advanced on how these coincidences may “explain“ or “solve“ the well-known information loss puzzle. The idea[(1)] that very massive string excitations should represent black holes has been better substantiated by analysing massive BPS states that, as known, have properties that are not renormalized, i.e. do not depend on the coupling strength.

In the weak string coupling (g) regime, D-branes in four[(2)] and five[(3)] dimensions with a convenient number of charges have been studied. BPS states have been counted as well as nearly BPS states for certain regions of moduli space where perturbative computations are feasible[(4)]. Decay rates have also been computed[(5)]−by averaging over the many initial states - and shown to have, a typical thermal distribution. The moduli independence of these results allow the conjecture[(6)] of their validity beyond the moduli region where they were computed. And their g independence (also suggested by non-renormalization arguments[(7)]) may imply that they could be continued beyond the weak coupling regime.

[a] The content of this note, even if with slightly different wording, was sent to the archives as hep-th 9706157. Several discussions since then, specially in occasion of the Spinoza Meeting on Quantum Black Holes (Utrecht 29 June - 3 July 1998) have shown the convenience of its publication

An independent treatment - on totally different grounds - of the strong coupling regime substantiates that impression. The large coupling description of the 4 and 5 dimensional systems just discussed is found by solving the 10-d supergravity equations after reduction on the same compact manifold used for the D-brane description. The solution generates a metric[8] that depends on parameters that are related to the charges through the moduli of the compact manifold. The metric shows an event horizon even in the extreme limit; its area in this limit gives the Beckenstein-Hawking entropy of extremal b.h. This entropy and the ADM mass coincide exactly with the mass and entropy (given by the log of the state multiplicity) of the BPS state with the same charges as computed from D-branes in the small coupling regime.

For nearly extremal b.h. the entropy, the rate and the spectrum of evaporation[9] - obtained by solving wave equations in the corresponding metric background - coincide again[5] with those computed for small g. And, even more remarkably, also deviations from black body spectrum agree[10]. These magic coincidences between such different calculations gave confidence to the g continuation between a unitary D-brane description and the conventional black hole with its information loss.

Different interpretations of this apparent contradiction have been advanced. Hawking questioned the D-brane formalism because the causal properties of space time are not properly taken into account. And even more so having shown[11] that the inconsistency cannot be assigned to the lack of identificability of D-brane states due to their prompt decay. String theorists[12] favour the attitude that black body radiation is only an approximation and that the connection with unitary D-brane formalism guarantees information retrieval in b.h. evaporation. This even more so since duality indicates situations that have flat unitary realizations for $g<<1$ as well as for $g>>1$ with a b.h. intermediate region with quite different space time geometry but with an alledgedly common spectrum.

Let me share the consensus of a smooth g behaviour by considering an S-matrix approach where a continuation has a clear meaning and let me start in the small coupling regime where a perturbative string approach is granted.

If over a well-defined BPS state impinges from far away - where for small g the space is flat - a well-defined quantum state (say a graviton) the S matrix, calculable by perturbative string theory, will be unitary. It describes the absorption of the graviton generating open strings on the D-brane then decaying, through an arbitrary number of steps, to some BPS state plus outgoing closed string ground states (as gravitons and scalars).

The physical content of this large set of S matrix elements is better analysed by computing final state correlation functions that give semi-inclusive

quantities as multiplicities, spectra or multiparticle correlations. Old string theorists will remember the techniques used to directly compute these correlators from multiparticle amplitudes, order by order in g. They will also recall, however, the need to recurr to the full set of final state correlators in order to disentangle the high degeneracy of initial states. This means that if we change the choice of the initial BPS state (among the very many degenerate ones) or if we consider two gravitons impinging instead of a single one, or if we change g, all these correlators will be modified in a non-trivial and coherent way. The whole set of correlators represent the complete memory of the original state.

The result we discussed before concerning the Hawking spectrum, tells us that if we now perform an average over the very many possible initial (degenerate) states, all multiparticle correlators will average to zero apart from the single particle spectrum that - by energy conservation - averages to a thermal one. And this for each g, thus order by order in the string loop expansion. This is perhaps not too surprising: the average over the very many degenerate microstates washes out all information over the initial identity leading to the informationless black body radiation. Let me stress that this average over degenerate microstates is implied in any classical limit.

In increasing g towards a black hole regime, it is the quantum S matrix that should be analytically continued. Its analytic structure may be very complex, with new singularities being eventually formed, but with unitarity preserved with the concurrence - as before - of the very many phases that depend on the initial (black holish) microstate. These are essential in order to determine the many non-trivial correlation functions. The fact that these averaged to zero independently from g for small g - giving the same Hawking spectrum of the large g regime - shows that no new physics (new singularity in the g continuation) has to be invoked in order to understand the spectrum and entropy of macroscopic black holes (statistical collection of microscopic states).

This same reasoning, however, shows that the decay spectrum of a single microstate differs crucially from a black body one. This was the case for all small g, thus for all g by continuation in a context in which no new physics is evoked. We thus expect for a "would be black holish" microstate, far from vanishing correlators that encode the whole information about the (coherent) formation process.

It is apparent that a single microstate - even in the large g regime - has not much to do with a black hole and that it is only the decoherence implied by the macroscopic description (i.e. average over microscopic states) that generates the black hole physics. Such a statement needs, however, a parallel understanding of why it is only at the macroscopic level that the geometrical

interpretation of general relativity emerges with its causal properties, singularities and event horizons.

Superstring theory contains gravity in the infrared limit; for frequencies much smaller than the string scale, the Einstein classical equations appear as the non renormalization (β=0) condition. At the quantum level, however, fluctuations at the string scale will generate all other (massive) background fields which will appear (thanks to the β=0 condition) in a large system of coupled equations together with the metric field. In a more common language, this implies a very large number of quantum hairs. These many non-metric coupled fields, that inhibit a geometrical space time description, are expected to have quickly varying phases so as to be averaged out in the decoherence procedure implied by classical (or mesoscopic) physics. This is perhaps not surprising, superstrings are pregeometric quantum theories in which even a space time description is not warranted: Xμ are operators and it is only at the mesoscopic level (in which quantum string fluctuations are averaged away) that they appear as coordinates parametrizing a metric space. It is thus this decoherence that generates a geometrical space time description (i.e. general relativity) and with it, causal properties event horizons and the paraphernalia of black hole physics.

The consideration up to now of charged extremal or near extremal black holes or, in the string language, solitonic D branes which are BPS or quasi BPS states, was an essential step in order to identify and count stable or nearly stable states. This allowed the consideration of S matrices with well-defined quantum initial states, excited in the process and evaporating back to stable final states.

For unstable states (high string excitations or Schwarzschild b.h.) a consistent quantum treatment has to comprehend both formation and decay. In the small g regime this is anyhow the conventional approach of perturbative string amplitudes. In the b.h. regime it implies the consideration at a consistent quantum level of both the formation and evaporation of a b.h, thus avoiding, ultimately, the hybrid theoretically procedure of quantizing in the presence of a purely classical solution. It is obvious that one might unambiguously prepare imploding states (spherical waves or even high energy low mass particles colliding at very small impact parameter) at large separations where a flat metric is granted. At a classical level and even at a semiclassical one [13] (i.e. with radiation) black holes would be formed in these conditions losing memory of the state they originated from.

This is not the case at the quantum level. Again, at small g where everything is in principle calculable, final state correlators are far from vanishing and contain all the information needed to disentangle the initial state (unitar-

ity). No new physics has to be invoked in order to continue to the large g black hole regime: it is the presence of non metric fields of arbitrary high tensorial rank that avoids the Schwarzschild singularity of the usual general relativistic (metric) solution. And, again, it is the mesoscopic decoherence implied by averaging over microstates, that on one hand averages out the correlators that carry all the microscopic information thus leading to a black body (or approximate black body) spectrum and, on the other hand, washes away the non metric fields thus leading to a geometric space time general relativistic picture with causal properties, horizons, black holes, etc.

At this level it may be sound to ask if this decoherence may be avoided in a gedanken experiment so as to show the full quantum structure of the fundamental gravity theory. Could, for instance, a classically expected black hole be avoided by preparing well-defined coherent imploding states? In my opinion the infrared properties of gravitation may jeopardize this possibility. Indeed, it seems even conceptually hard to avoid incoherent arbitrary soft gravitons and, with them, their high decoherence power due to the very large density of microstates.

Let me stress the important role that the high degeneracy of states had in the smooth merging of a unitary microstate description into a black hole macrostate one. Qualitatively, it is apparent that a degeneracy that grows exponentially with the mass is a border-line between a tendency of states, interacting through vertex operators, to split as in particle physics or join as for b.h. due to the final states multiplicity. One would be tempted to think that consistent fundamental theories of quantum gravity have to have such a degeneracy in order to lead to macroscopic general relativity. No wonder, in this sense, that superstring theory is a good candidate while supergravity is not. It would be interesting to understand how other proposals that have been advanced, such as topological gravity, may solve this problem in their attempt to qualify as possible consistent theories of quantum gravity.

This work was partially supported by EC Contract no. ERBFMRXCT960090 and by the research grant on Theoretical Physics of Fundamental Interaction of the Italian Ministry for Universities and Scientific and Tecnological Research.

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